GLACIOLOGY

Johnathan Thom (in black) of the University of Wisconsin at Madison and Doug MacAyeal (in red) of the University of Chicago install on the large tabular iceberg B-15A a tower with instruments that will relay position, temperature, wind speed, pressure and humidity to a satellite. Scientists will be able to track the conditions on and around the iceberg as it makes its way through the waters of Antarctica. *(NSF photo by Josh Landis)*

Ice is the defining characteristic of Antarctica, indisputably. The entire continent (with a few exceptional areas such as the McMurdo Dry Valleys and some lakes and mountains) is covered by a "sheet" of ice that has been laid down over eons, if the term sheet can be used to describe a dynamic mass several thousand meters (m) thick, larger than most countries, rising over 2,000 m above sea level (peaking in an ice dome in the east nearly twice that high), and heavy enough to depress the bedrock beneath it some 600 m. Actually there are two sheets - the much larger East Antarctic Ice Sheet that covers the bedrock core of the continent and, beyond the Transantarctic Mountains, the smaller, marine-based West Antarctic Ice Sheet that overlays a group of islands and waters.

The Glaciology Program is concerned with the history and dynamics of the antarctic ice sheet; this includes research on near-surface snow and firn, floating glacier ice (ice shelves), glaciers, ice streams, and continental and marine ice sheets. These species of ice facilitate studies on ice dynamics, paleoenvironments (deduced from ice cores), numerical modeling, glacial geology, and remote sensing. Some current program objectives include:

• correlating antarctic climatic fluctuations (from ice core analysis) with data from arctic and lower-latitude ice cores;

• integrating the ice record with the terrestrial and marine records;

• investigating the physics of fast glacier flow with emphasis on processes at glacier beds;

• investigating ice-shelf stability; and

• identifying and quantifying the relationship between ice dynamics and climate change.

History and evolution of the West Antarctic Ice Sheet, Marie Byrd Land.
Charles F. Raymond, University of Washington.

The West Antarctic Ice Sheet (WAIS) has been an object of intense study for years, yet much remains to be specified about its evolution and dynamics - and therefore its possible futures. Almost certainly, those potential futures are vital to the Earth's global climate and its ocean systems. Because its base consists of a series of archipelagos, the WAIS is a marine ice sheet. The Siple Coast Ice Stream system is a principal dynamic process by which the ice sheet drains ultimately into the Ross Sea. This seaward movement runs primarily through the Byrd subglacial trough, its flanks defined by the Ellsworth Mountains; such movement will usually leave behind tell-tale scars in the ice.

This project focuses on scar-like features in this region; some are well known, other margin scars are poorly constrained and need better dating, and still other as-yet unvisited scars require primary identification and exploration. To locate and map these features, we will use Advanced Very High Resolution Radiometer (AVHRR) and Radarsat image data, which will enable us to place them more exactly within the region's known topography.

Our goal for these initial data is a better description of the recent history of the Siple Coast glaciers, and a more coherent account how they were configured. For this, we will use low-frequency radio-echo sounding (RES) and high-frequency ground-penetrating radar (GPR) profiles to image internal layers and measure the depths of buried crevasses or disrupted layering. These depths, seen in the context of accumulation rates determined from shallow ice cores, will provide "shutdown" ages for when the margin features ceased actively flowing; that is, times after which they could not have formed. The field data should allow us to develop simple ice-flow models - for the margins and inter-ice stream ridges - during active shearing and after shutdown. One primary output of such models would be closer estimates than we have at present of the initial elevation of a given scar, and the corresponding ice-stream elevation, at the time of shutdown. (II-163-O)

Ice dynamics, the flow law, and vertical strain at Siple Dome.
William Harrison, University of Alaska, Fairbanks.

Ice flow near a divide such as Siple Dome is unique because it is predominantly vertical. As ice is deformed vertically, the vertical strain rate dominates and must be quantified in order to calibrate dynamic models of ice flow. Our project - a collaboration between the Universities of Alaska, Washington, and California, San Diego - is measuring the vertical strain rate (as a function of depth) at two sites on Siple Dome, Antarctica. We hope to develop a better analysis of the ice core than was possible from recent coring sites in central Greenland.

We are in the final of four years, using two relatively new, high-resolution systems to measure the core in hot-water drilled holes. These data, coupled with a determination of the flow-law, are used to interpret the shapes of radar internal layering as indicators of the accumulation patterns and dynamic history of Siple Dome over the past 10,000 years; an improved model should emerge. This model will provide a context in which to interpret the ice core drilled at Siple Dome - both the thicknesses of the annual layers (as indicative of annual accumulation rates) and the borehole temperatures.(II-164-O)

High precision borehole temperature measurements at Siple Dome, Antarctica, for paleoclimate reconstruction and ice dynamics studies.
Edwin D. Waddington and Gary D. Clow, University of Washington.

One of the procedures involved in ice coring is high-precision borehole temperature profiling. By constructing continuous temperature logs, scientists can develop data vital to paleoclimate reconstruction and ice dynamics studies. This project will work in the 1-kilometer (km) deep, fluid-filled Siple Dome borehole and in several 160 meter-deep holes along a 20-km north-south transect across Siple Dome. The borehole temperature data will be used to:

• establish the conductive heat flux across the basal interface of the ice sheet;

• reconstruct the surface temperature history at Siple Dome, using geophysical inverse methods known as borehole paleothermometry;

• constrain how thick the ice sheet was during the late Wisconsin, the magnitude of the Wisconsin/Holocene deglacial warming, and the background geothermal heat flux;

• determine calibration constants for the oxygen-isotope paleothermometer at Siple Dome in the past; and

• establish the spatial variability of surface temperature over the last century on the 20-km scale near the main drill site.

We expect the results to provide information needed to assess the short-term stability of the West Antarctic Ice Sheet; also to improve estimates of the pore close-off ages in the past, which should in turn provide a more accurate age-scale for the Siple Dome ice core. Ultimately, this work should enhance our understanding of the magnitude of past temperature changes at this significant southern hemisphere site.

In the austral summer of 2001-2002, we begin two other aspects of the project, in collaboration with the U.S. Geological Survey (USGS).

(1) Borehole fingerprinting - vertical strain, firn compaction, and firn depth-age scales. This 2-year project will develop a new method for measuring vertical strain rates in firn. Such measurements in the firn can help to:

• describe the dynamics of firn compaction (a key factor in determining ice age/gas age difference estimates for ice cores);

• determine ice advection for borehole paleothermometry models; and

• date the shallow sections of ice cores, where ambiguities in chemical dating or counting annual layers compromise traditional dating methods.

Borehole fingerprinting has the potential to improve measurements of vertical strain in firn holes. Preliminary work, using an improvised logging system at Siple Dome, showed a series of optically bright and dark zones as the tool was moved up or down the hole. We will use a video logging tool to create a unique "optical fingerprint" of variations in the optical properties of the firn (with depth), as well as to track the movement and deformation of the features of this fingerprint.

(2) High-resolution borehole paleothermometry. We are also developing and testing digital probes for high-precision temperature measurements in boreholes in polar ice sheets. These measurements are key to obtaining calibrated paleotemperature records in the

polar regions. The current state-of-the-art system is the USGS Polar Borehole Temperature Logging System (PBTS), which uses analog probe technology coupled with an electronic package at the ice sheet surface. Strong winds encountered in the field, however, can disturb the recording electronics. Probes that transmit digital signals up the cable would not be affected by these surface conditions and are more likely to provide quality data and improve the efficiency of field operations.

We are adapting a recently designed digital probe for use with the PBTS system in cold temperatures in ice-core drilling fluids. These probes streamline both the hardware and the procedures required for the current analog system. This austral summer, we will calibrate these new digital probes alongside the currently used sensors and test them at Siple Dome. We expect to describe this working borehole temperature-logging system in the *Journal of Glaciology*, gaining insight on the new digital probes, how the system compares to current technology, and the new research opportunities that digital probes can offer. (II-171-O)

Construction and operation of biospectrologger in a borehole in polar ice.
Buford Price, University of California, Berkley.

Microbes adapted to oligotrophic, low-temperature environments - lakes that lack plant nutrients and usually contain plentiful amounts of dissolved oxygen without marked stratification - are found in glacial ice, frigid lakes, in permafrost, and in cold, deep ocean water and sediments. Of these various sinks, polar ice contains the lowest concentrations of such microbes (from a few hundred to about 10^4 cells per cubic centimeter), which were probably transported by wind into the atmosphere, precipitated with snow, and compacted into ice. The great majority of these are dormant or dead.

Trying to cultivate microbes recovered from such ice cores is a hit-or-miss proposition, yielding colony-forming units in only a fraction (between about 10^{-4} to 10^{-2}) of dormant cells. Chemical, physical and biological models indicate that as many as 10^3 microbes per cubic centimeter are able to extract sufficient energy from acids (confined in narrow liquid veins in otherwise solid ice) to survive for a few thousand years or a smaller population for a correspondingly longer time. No search has yet been carried out for living bacteria in such liquid veins.

We plan to construct and operate a biospectrologger at Siple Dome, Antarctica, during the 2001-2002 field season as part of an ongoing borehole logging program at that site. Such an optical device has already been developed and tested for measuring dust in polar ice, but we will explore whether the same general principle can be expanded to study microbes and biomolocules - as a function of depth - in glacial ice. (IO-122-O)

Iceberg drift in the near-shelf environment, Ross Ice Shelf, Antarctica.
Douglas MacAyeal, University of Chicago.

Icebergs command a lot of attention. The Titanic disaster at sea illustrates only one important reason. Such a massive piece of glaciology on the move is a process that scientists would like to have better models for. One theoretical benefit entails harnessing the extraordinary freshwater volume of large tabular icebergs - possibly even harvesting it - as a natural resource of potential economic value, especially for water-poor regions of the earth. And though feasibility studies of towing icebergs to such areas in need have largely been dismissed as science fiction, it is tantalizing to realize that tabular icebergs commonly travel thousands of miles as a result of natural processes. Might a better understanding of the behavior and dynamics of icebergs one day lead to such a boon of human economic and social value?

The recent calving of an extraordinarily large iceberg (designated B-15) from the Ross Ice Shelf presents a unique opportunity to measure the processes - such as wind-driven and thermohaline currents, tides, sea ice, and winds - that control the drift of large tabular icebergs. Such an event rarely occurs within the logistical reach of the U.S. Antarctic Program, so this is an opportunity to study iceberg drift, as well as other aspects of iceberg behavior that are associated with the long-term stability of the antarctic environment.

In this second year of our investigation, we plan to:

• deploy three geodetic-quality GPS receivers (provided by UNAVCO) on iceberg C-16 for about 7 weeks, at the vertices of an equilateral triangle (with one-kilometer legs) somewhere near the center of C-16.

• install 2 AWS/GPS tracking stations (that is, standard meteorological "towers" about 20 feet tall) at two of the three vertices of the equilateral triangle (referenced above) and to retrieve in late January geodetic-quality GPS receivers that were installed in December.

• try to locate iceberg B-15a, and service and upgrade three AWS/GPS tracking stations currently deployed there.

The data we expect from these instruments should constrain parameters that will improve the models of iceberg drift, as well as our ability to predict calving events and the subsequent iceberg drift trajectories. (IO-190-O)

Deglacial chronology of the northern Scott Coast from relative sea-level curves.
Brenda Hall, University of Maine.

A key unresolved question in antarctic glaciology concerns the stability of the marine-based West Antarctic Ice Sheet (WAIS). Marine-based means that (unlike the base of the East Antarctic Ice Sheet sitting on a lithospheric plate) the substratum for the WAIS is a series of archipelagoes, such that the sheet at its relatively fixed position is grounded on the continental shelf - in the northwestern Ross Sea Embayment off the northern Scott Coast - with plate boundaries nearby. As deglaciation began after the last glacial maximum (LGM), the WAIS eventually became unmoored. Scientists believe this was likely the first area of the shelf to become free of grounded ice. Learning how and when (and in what sequence) this has occurred in the past is a critical step for isolating the mechanisms (sea level, climate, ocean temperature, and internal dynamics) that control WAIS dynamics.

Thus the northern Scott Coast is of particular interest to researchers looking for mechanisms that may have triggered the key stages of deglaciation. But an important first step is to better constrain the age of structures where the inquiry is focused. The Barbados coral record suggests the initial retreat from the Ross Sea Embayment may have begun as early as 17,000 years ago. In contrast, recent glacial geologic mapping and relative sea-level work from the southern Scott Coast suggests that deglaciation here is more recent, during the Holocene (the last 11,000 years), with southward grounding-line migration past Ross Island shortly before 6,500 years ago [carbon-14 (^{14}C) dating]. This chronology suggests that rising sea level could not have driven grounding-line retreat to the Siple Coast, because deglacial sea-level rise essentially would already have occurred by mid-Holocene.

To begin to resolve this conflict, one deficiency in the southern Scott Coast work might be corrected. Those data cannot differentiate among the possible triggering mechanisms because they come from 450 kilometers south of the LGM grounding-line position. We will try to overcome this by constructing relative sea-level curves on a transect along the northern Scott Coast. We hope to get the ages for this work from accelerator mass spectrometer ^{14}C dates of seal skins and shells within raised beaches. These curves should tell us when the grounded ice from the northwestern Ross Sea Embayment cut loose. (IO-196-M)

Characterizing the onset of ice stream flow: A ground geophysical field program.
Sridhar Anandakrishnan, University of Alabama.

Ice streams of the Ross Sea Embayment are the principle force by which the interior West Antarctic Ice Sheet (WAIS) is drained, moving vast quantities of ice rapidly to the front of the Ross Ice Shelf, where they are calved off as icebergs. These ice streams provide a buffer between the interior ice and the floating ice shelves. For antarctic ice streams on the Siple Coast, the transition from no-sliding (that is, all internal deformation) to motion dominated by sliding is defined as the "onset-region." To fully understand (and adequately model) the WAIS, we must have a better understanding of this onset region, which means learning the reasons for their fast flow and the factors controlling their current grounding-line, margin and head positions. The lateral margins of the ice streams are also a transition that needs better explanation.

Hypotheses on controls of the location of the onset region range from the "purely-glaciologic" to the "purely-geologic." Until the basal boundary conditions - roughness, wetness, till properties - are specified, and a good subglacial geologic map that shows the distribution, thickness, and properties of the sedimentary basins is drawn, ice sheet models will remain incomplete.

These parameters can be estimated from seismic, radar and other geophysical methods. We will study the transition region of ice stream D in detail with this coupled geophysical experiment. We will also select other locations on ice streams C & D to study, compare, and contrast conditions with the main site on ice stream D. Site-selection for the main camp will be based on existing radar, GPS and satellite data, as well as input from the modeling community. (IO-205-O)

Glacial history of Ridge AB.
Howard Conway, University of Washington.

Scientists do not fully understand a basic aspect of the stability of the West Antarctic Aice Sheet - how the configuration and activity of the drainage system is changing. Ridge AB provides a key area of study because:

• While previous studies of inter-stream ridges in West Antarctica have revealed much information about the history of the surrounding ice streams, there remains an "information-hole" in the southern sector of the ice sheet. We believe a targeted study of Ridge AB will reveal new information about recent changes in the configuration and activity of Ice Streams A and B.

• Geologic evidence from Reedy Glacier indicates that ice near Ridge AB was about 700 meters (m) thicker during the last glacial maximum. This helps constrain the magnitude of thinning that has occurred through the Holocene and opens the possibility of linking the history of the West Antarctic Ice Sheet to the geologic record in the Transantarctic Mountains.

We plan to first map spatial variations of internal layering, buried crevasses, surface velocity, and accumulation rate, using high- and low-frequency radar systems, GPS surveying methods, and short (20 m) firn cores. These diagnostic measurements will be put into ice-flow models to infer the glacial history of Ridge AB and the surrounding ice streams. The history will be interpreted in the context of the histories that are emerging from the other inter-ice stream ridges, as well as the geologic evidence from Reedy and other outlet glaciers in the Transantarctic Mountains. We hope these explorations will enhance scientific understanding of the evolution of the WAIS drainage system.(IO-210-O)

Deposition of HFC degradation product trifluoroacetate in antarctic snow and ice.
Joseph McConell, Desert Research Institute.

Pursuant to the 1987 Montreal Protocol and the 1995 Clean Air Act in the United States, the threat to global ozone posed by migration into the atmosphere of chlorofluorocarbons (CFC) has led to the release into the biosphere of some worrisome substitutes. One of these, trifluoroacetate (TFA), is a highly persistent, atmospheric degradation product of the halogenated ethane derivatives (HCFC, HFC).

As this class of chemicals is now in widespread industrial use, there is growing concern that TFA will accumulate in aquatic ecosystems. Extant data on the pre-industrial (background, or baseline) concentration of TFA in meteoric and surface waters, including antarctic ice, are ambiguous; thus the impact of anthropogenic TFA on these background concentrations is hard to specify. Ice core records, however, can provide a useful proxy for background and thus enable models to be developed for anthropogenic TFA deposition.

Our primary objective is to use ice cores and snow pits at South Pole to develop a record of TFA deposition for the last millenium, focused especially on the past 20 years. This pre-industrial to present record of TFA in near-surface snow and ice at South Pole and in West Antarctica will be unique. It should elucidate the origin, transport, and fate of this contaminant over Antarctica and - possibly - the globe. More generally, it enhances the context for assessing potential impacts on antarctic ecosystems from the natural and anthropogenic sources, by providing vital data on the regional and long-range movement, and the eventual fate, of contaminants. (IU-123-O)